WHY LOW–MASS BLACK HOLE BINARIES ARE TRANSIENT

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ABSTRACT

We consider transient behavior in low–mass X–ray binaries (LMXBs). In short–period neutron–star systems (orbital period $\lesssim 1$ d) irradiation of the accretion disk by the central source suppresses this except at very low mass transfer rates. Formation constraints however imply that a significant fraction of these neutron star systems have nuclear–evolved main–sequence secondaries and thus mass transfer rates low enough to be transient. But most short–period low–mass black–hole systems will form with unevolved main–sequence companions and have much higher mass transfer rates. The fact that essentially all of them are nevertheless transient shows that irradiation is weaker, as a direct consequence of the fundamental black–hole property – the lack of a hard stellar surface.

Subject headings: Subject headings: accretion, accretion disks — binaries: close — instabilities — black hole physics

1. INTRODUCTION

The circumstantial evidence that many soft X–ray transients (SXTs) contain black holes is now very strong. Several of these systems have been found to have mass functions so large that the compact star's mass exceeds any likely value for the maximum mass of a neutron star. By elimination it is generally believed that this star must be a black hole. The incidence of such black–hole candidate systems (BLMXBs) among SXTs with known orbital periods (8 out of 14) is much greater than any likely estimate of their incidence among persistent LMXBs (1 out of 29). It has been suspected for some time that this is a consequence of the lower mass transfer rates expected in black–hole systems (Mukai 1994). At the rates expected for main–sequence companions the accretion disks in these systems would be unstable, giving rise to the X–ray outbursts (e.g. Cannizzo et al. 1982, Lin & Taam 1984). However this would also be true of most neutron–star systems (NLMXBs), and yet the majority of these are observed to be persistent. In this context van Paradijs (1996) pointed out the crucial importance of irradiation of the disk by the central accreting source in determining its

stability. For a central point source this leads to a much tighter upper limit on the mass transfer rate allowing transient behavior, which is satisfied by all observed NLMXBs.

Following this, King, Kolb & Burderi (1996; hereafter KKB) and King et al. (1997) showed that this more stringent condition still makes most long–period NLMXBs with a low–mass giant donor (orbital period $P \gtrsim 1$ d) transient, whereas short–period NLMXBs with a main–sequence donor ($P \lesssim 1$ d) are transient only if the companion star is significantly nuclear–evolved before mass transfer begins. The fact that a non–negligible fraction of such systems are nevertheless observed to be transient imposes very tight constraints on the formation of NLMXBs. These turn out to hold in practice (King & Kolb 1997), strengthening one's belief in the consistency of the whole picture: NLMXBs can only form with companions sufficiently evolved that many of them have low mass transfer rates and appear as SXTs. However, while irradiation brings clarity to the picture of NLMXBs, it appears to complicate matters for the black–hole systems. For here the formation constraints are far weaker than for NLMXBs. In particular survival of the binary after any supernova explosion forming the compact object is virtually guaranteed for a black hole, in stark contrast to the neutron–star case; there is no apparent reason why most short–period BLMXBs should not form with completely unevolved companion stars. These systems would have mass transfer rates well above the limit for transient behavior in NLMXBs. This fact would apparently force us to predict the existence of large numbers of persistent BLMXBs, quite contrary to observation.

We address this problem here. We shall show that the resolution of the apparent paradox is that irradiation differs sharply for neutron–star and black–hole systems. In the latter case, the lack of a hard stellar surface means that the central source is the inner region of the accretion disk itself. The small solid angle subtended by these regions at the outer parts of the disk greatly weakens the stabilizing effect of irradiation, allowing essentially all BLMXBs to be transient. It thus appears that transient behavior gives direct confirmation of the fundamental black–hole property precisely in systems whose mass estimates already suggest the presence of black holes.

2.   DISK INSTABILITIES IN NLMXBs

The conditions for disk instability in LMXBs have been considered in detail by van Paradijs (1996), KKB, and King et al. (1997), and we summarize their conclusions here. If a steady state exists in which all of the disk is above the hydrogen ionization temperature $T_H \sim 6500$ K, the instability will be suppressed and the source will appear as persistent. Viscous dissipation alone gives an effective temperature $T_{\rm visc}$, with (e.g. Frank et al. 1992)

$$T_{\rm visc}^4 = \frac{3GM\dot{M}}{8\pi\sigma R^3} \tag{1}$$

at disk radii R much larger than that of the central object (M is the mass of this star, $\dot{M}$ the accretion rate, G the gravitational constant and σ the Stefan–Boltzmann constant). Irradiation

plays an important role in potentially raising the disk's surface temperature T above T_{visc}, i.e.

$$T^4 = T_{\mathrm{visc}}^4 + T_{\mathrm{irr}}^4. \tag{2}$$

For a point source at the center of the disk, the irradiation temperature T_{irr} is given by

$$T_{\mathrm{irr}}^4 = \frac{\eta \dot{M} c^2 (1-\beta)}{4\pi\sigma R^2} \frac{H}{R} \left(\frac{\mathrm{d}\ln H}{\mathrm{d}\ln R} - 1 \right). \tag{3}$$

Here η is the efficiency of rest–mass energy conversion into X–ray heating, β is the X–ray albedo, and $H(R)$ is the local disk scale height. Since T always decreases with R, the condition $T > T_H$ for steady accretion is most stringent at the outer edge R_d of the disk. We define a critical accretion rate $\dot{M}_{\mathrm{cr}}$ by the equation

$$T(R_d) = T_H. \tag{4}$$

Formally we define also the critical rate $\dot{M}_{\mathrm{cr}}^{\mathrm{visc}}$ in the absence of irradiation ($T_{\mathrm{visc}}(R_d) = T_H$), and the critical rate $\dot{M}_{\mathrm{cr}}^{\mathrm{irr}}$ for fully irradiation–dominated disks ($T_{\mathrm{irr}}(R_d) = T_H$). These definitions imply that

$$\frac{1}{\dot{M}_{\mathrm{cr}}} = \frac{1}{\dot{M}_{\mathrm{cr}}^{\mathrm{irr}}} + \frac{1}{\dot{M}_{\mathrm{cr}}^{\mathrm{visc}}}. \tag{5}$$

Thus the disk instability is suppressed for $\dot{M} > \dot{M}_{\mathrm{cr}}$ and we can try to discriminate between steady and outbursting systems by checking this condition, equating the accretion rate $\dot{M}$ to the mass transfer rate $-\dot{M}_2$ from the companion. In CVs, $T_{\mathrm{irr}} \ll T_{\mathrm{visc}}$, and this procedure correctly predicts that all disk–accreting systems below the period gap should be dwarf novae. In NLMXBs T_{irr} is all–important: the last two factors on the rhs of (3) are typically $\propto H/R \sim$ constant (see below), so T_{irr}^4 falls off only as R^{-2} compared with R^{-3} for T_{eff}^4. At the outer disk edge R_d we thus expect $T_{\mathrm{irr}} > T_{\mathrm{visc}}$, giving a critical accretion rate $\dot{M}_{\mathrm{cr}}$ which is typically almost two orders of magnitude lower at a given orbital period for main–sequence donor systems (see below and Fig. 3).

It is sometimes suggested that the outer disk is not affected by irradiation, either because the disk is convex and shadows its outer parts, or because the outer layers form an optically thin corona above the disk (e.g. Tuchman, Mineshige & Wheeler 1990; Cannizzo 1994). In both cases $T \simeq T_{\mathrm{visc}}$ rather than (2). However, the fact that $\dot{M}_{\mathrm{cr}}$ (from eq. 5) rather than $\dot{M}_{\mathrm{cr}}^{\mathrm{visc}}$ separates transient from persistent NLMXBs (van Paradijs 1996), as well as the high optical to X–ray flux ratio observed in LMXBs, is strong evidence for the dominant role of irradiation.

Thus assuming that the outer disk temperature is controlled by irradiation, we conclude that short–period neutron–star transients must have relatively low mass transfer rates. KKB deduced that they must have companions which are nuclear–evolved before mass transfer begins, even at very short periods where one might otherwise expect a completely unevolved lower–main–sequence companion. Since a significant fraction of NLMXBs are transient this peculiar condition must follow from the constraints on the formation of NLMXBs. King & Kolb (1997) indeed show that this is true if the average kick velocity imparted on the neutron star at birth is small. To prevent disruption the binary has to retain at least one–half of its mass after the helium star supernova

(SN) which forms the neutron star. The neutron star probably has a mass close to $1.4 M_\odot$ at birth, favoring the survival of systems with a massive companion and a low mass neutron star progenitor. To accommodate such a low mass helium star, the pre–SN orbit must have been very wide, hence also the post–SN orbit. The corresponding long detached post-SN evolution causes the secondary to be nuclear–evolved at turn–on of mass transfer.

By contrast it is clear that no such constraint can hold for black–hole systems: even if a supernova occurs, which is unclear, the black hole can easily bind more than one–half of the progenitor mass, thus leaving the companion mass effectively unconstrained. Hence we expect that most short–period BLMXBs will form with unevolved main–sequence companions. Magnetic braking and gravitational radiation will then drive mass transfer rates considerably higher than the $\dot{M}_{\rm cr}$ deduced for NLMXBs above, and one would at first sight expect the vast majority of short–period BLMXBs to be persistent X–ray sources, in complete contradiction to what is observed.

3.   DISK INSTABILITIES IN BLMXBs

The answer to this difficulty is the fact that irradiation is much weaker if the accreting object is a black hole rather than a neutron star. This is already mentioned in the seminal paper on accretion disk structure by Shakura & Sunyaev (1973). The reason is that in the black–hole case the central object has no hard surface, and so cannot act as a point source for irradiation as assumed in the derivation of (3). Of course, a comparable luminosity is released in the inner part of the accretion disk surrounding the hole, but this is a flat surface lying in the disk's central plane, and thus almost parallel to the surface layers of the outer regions of the disk. A full calculation is complex, but it is clear that the solid angle subtended by the inner disk is smaller by a factor $\sim H/R$ than assumed in (3). We can neglect relativistic beaming effects for irradiation of the outer disk (Cunningham 1976, Zhang et al. 1997). For simplicity we therefore replace (3) by

$$T_{\rm irr}^4 = \frac{\eta \dot{M} c^2 (1-\beta)}{4\pi\sigma R^2} \left(\frac{H}{R}\right)^2 \left(\frac{{\rm d}\ln H}{{\rm d}\ln R} - 1\right) \tag{6}$$

in the black–hole case. With this change, (4) now defines a new (higher) critical mass transfer rate $\dot{M}_{\rm cr}$, which we must compare with the rates expected from binary evolution.

To evaluate $\dot{M}_{\rm cr}^{\rm irr}$ we assume that R_d is about 70% of the primary's Roche lobe radius R_L, which in turn is a fraction f_1 of the binary separation a; f_1 depends only on the ratio $q = M_2/M_1$ of donor mass M_2 to primary mass M_1. For $T_{\rm irr}$ we need an estimate of $H(R)$. Neglecting internal viscous dissipation and assuming an isothermal vertical disk structure it is easy to show (e.g. Cunningham 1976, Fukue 1992) that $H \propto R^{9/7}$ if $T_{\rm irr}$ is given by (3), and $H \propto R^{4/3}$ with $T_{\rm irr}$ from (6). In reality the disk is not isothermal and the slope is closer to the standard law $H \propto R^{9/8}$ for unirradiated discs. We adopt 43/36 and 45/38 for the BH case (6) and the neutron star case (3), respectively (cf. Burderi, King & Szuszkiewicz 1997). Furthermore, observations of LMXBs indicate $H/R \simeq 0.2$ and $\beta \simeq 0.9$ (de Jong et al, 1996, and references therein). Using these results and $\eta = 0.2$ in (4, 6)

gives

$$\dot{M}_{\text{cr}}^{\text{irr}} = 1.34 \times 10^{-10} \, f_1^2 (m_1 + m_2)^{2/3} \, P_h^{4/3} \, \text{M}_\odot \text{yr}^{-1} \,, \tag{7}$$

with $m_1 = M_1/\text{M}_\odot$, $m_2 = M_2/\text{M}_\odot$ and $P_h = P/\text{hr}$.

4. MASS TRANSFER RATES IN BLMXBs

At periods longer than about a day, mass transfer in LMXBs is driven by the nuclear expansion of the secondary. For low–mass systems with this star on the first giant branch a simple core–envelope description is available, and gives the mass transfer rate as

$$-\dot{M}_2 = \frac{7.26 \times 10^{-10}}{\zeta_{\text{eq}} - \zeta_{\text{L}}} \, m_2^{1.46} \, P_d^{0.93} \, \text{M}_\odot \text{yr}^{-1} \tag{8}$$

(cf. King et al. 1997, King 1988). Here P_d is the orbital period in days, ζ_{eq} the thermal equilibrium mass–radius exponent (taken as 0) and $\zeta_{\text{L}} \simeq 2M_2/M_1 - 5/3$ the secondary's Roche lobe index. Transient behavior requires $-\dot{M}_2 < \dot{M}_{\text{cr}}$, which from (1), (5), (7) and (8) translates into a lower limit on M_1/M_2 for given P and M_2 (Fig. 1). The only persistent BH systems are those with an unusually low BH mass ($\lesssim 3\text{M}_\odot$) and high companion mass ($\gtrsim 1.5\text{M}_\odot$), putting them close to mass transfer instability. Such systems evolve quickly to the transient regime as the companion mass is reduced. This can be seen in Fig. 2, where we show the mass transfer rate as a function of orbital period along typical evolutionary sequences. This of course is not surprising in the light of the results of King et al. (1997) who showed that the NLXMB prescription (3) already makes most systems transient. We conclude that essentially *all long–period BLMXBs should be transient.*

At short binary periods mass transfer is driven by angular momentum loss via magnetic braking and gravitational radiation. In contrast to the nuclear–evolution case the mass transfer rate here is quite sensitive to the primary mass M_1. First, larger M_1 raises the orbital angular momentum of the binary as $J \propto M_1^{2/3}$ for $M_1 \gg M_2$: if the angular momentum loss rate $\dot{J}$ is independent of M_1 (as is the case for magnetic stellar wind braking) the transfer rate is reduced as $-\dot{M}_2 \propto M_1^{-2/3}$, On the other hand we know that angular momentum loss via gravitational radiation actually increases, with $-\dot{M}_2 \propto M_1^{2/3}$. Using the form of Verbunt & Zwaan (1981) for the magnetic braking rate, with the radius of gyration set to $(0.2)^{1/2}$ and the calibration parameter to unity, and the standard form (e.g. Landau & Lifschitz 1958) for the gravitational radiation losses, the mass transfer rate is $-\dot{M}_2 = \dot{M}_{\text{MB}} + \dot{M}_{\text{GR}}$, with

$$\dot{M}_{\text{MB}} = \frac{1.08 \times 10^{-7}}{\zeta_{\text{eq}} - \zeta_{\text{L}}} \, \frac{(m_1 + m_2)^{1/3} m_2^{7/3}}{m_1} \, P_h^{-2/3} \, \text{M}_\odot \text{yr}^{-1} \,, \tag{9}$$

and

$$\dot{M}_{\text{GR}} = \frac{2.52 \times 10^{-8}}{\zeta_{\text{eq}} - \zeta_{\text{L}}} \, \frac{m_1 m_2^2}{(m_1 + m_2)^{1/3}} \, P_h^{-8/3} \, \text{M}_\odot \text{yr}^{-1} \,. \tag{10}$$

($\zeta_{\text{eq}} \simeq 1$, $\zeta_{\text{L}} \simeq 2M_2/M_1 - 5/3$ as above).

In Fig. 3 we plot the mass transfer rate and critical rate (7) as a function of orbital period for representative evolutionary sequences with an unevolved secondary for different initial BH mass $m_1 = 2, 5$ and 10. Magnetic braking is assumed to operate only as long as the secondary has a radiative core. This leads to a detached phase ("period gap") when the secondary becomes fully convective, followed by the resumption of mass transfer below the period gap. BLMXBs with unevolved donors above the detached phase ($P \gtrsim 3$ h) are transient if the BH mass is $\gtrsim 5 \mathrm{M}_\odot$, whereas at shorter periods ($P \lesssim 2$ h) BLMXBs are transient for any reasonable BH mass. We note, however, that the critical transfer rate is only slightly higher than the secular mean transfer rate in systems close to the period minimum and the upper edge of the detached phase for all BH masses. In view of the uncertainties in (7), one would therefore not be surprised by the appearance of persistent BLMXBs (even with a $10 \mathrm{M}_\odot$ primary) at these periods.

We can get a rough analytic representation of this result by introducing a number of simplifications: Using

$$f_1 \simeq f_2 \left(\frac{M_1}{M_2} \right)^{5/12} \tag{11}$$

the ratio f_1 can be obtained to better than 8% for $0.001 < M_2/M_1 < 1$ from f_2, the secondary's Roche lobe radius in units of a, which in turn is given by $f_2 \simeq (8M_2/81(M_1 + M_2))^{1/3}$ (Paczyński 1971). Thus we have from (7)

$$\dot{M}_{\mathrm{cr}}^{\mathrm{irr}} \simeq 2.86 \times 10^{-11} \, m_1^{5/6} \, m_2^{-1/6} \, P_h^{4/3} \, \mathrm{M}_\odot \mathrm{yr}^{-1} \,. \tag{12}$$

We then set $\dot{M}_{\mathrm{cr}} = \dot{M}_{\mathrm{cr}}^{\mathrm{irr}}$, $\zeta_{\mathrm{eq}} - \zeta_{\mathrm{L}} = 8/3$ and assume $m_1 \gg m_2$.

For systems above the gap ($P_h \gtrsim 3$) we furthermore assume $-\dot{M}_2 \simeq \dot{M}_{\mathrm{MB}}$ and define the parameter $\hat{m}_2 = M_2/M_2(\mathrm{MS})$, where $M_2(\mathrm{MS})$ denotes the mass of a main–sequence secondary which fills its Roche lobe at a given orbital period ($P_h \simeq 8.1 M_2(\mathrm{MS})/\mathrm{M}_\odot$). Then we find from (12) and (9) as a condition for transient behavior

$$m_1 > 3.9 \, \hat{m}_2^{5/3} \, P_h^{1/3} \,. \tag{13}$$

Thus the minimum primary mass becomes even smaller if the main–sequence secondary is somewhat nuclear–evolved ($\hat{m}_2 < 1$).

For systems with a fully convective secondary ($P_h \lesssim 2$) we have $-\dot{M}_2 = \dot{M}_{\mathrm{GR}}$. Detailed models show that along the pre–period minimum evolution the relation $P_h \simeq k \, m_2^{2/3}$ holds, for any BH mass. The constant k is $\simeq 5.8$ for secondaries with a helium content $Y = 0.28$, and slightly larger for larger Y (as would be the case if the secondary was nuclear–evolved at turn–on of mass transfer at longer P). Hence we find from (12) and (10)

$$P_h \, m_1^{2/9} > 1.1 \left(\frac{5.8}{k} \right)^{13/3} \tag{14}$$

as a condition for transient behavior, insensitive to M_1 and always fulfilled.

It has recently been suggested that black hole SXTs might be inefficient accretors in quiescence. The inner part of the accretion disk would be replaced by a quasi–spherical ("advective") accretion flow taking the matter into the black hole before it has time to radiate (Narayan, McClintock & Yi 1996; cf. Katz 1977; Begelman 1978). It is unclear how the SXT outbursts themselves would be produced in this picture; but nevertheless it is important to note that our criterion $\dot{M} < \dot{M}_{cr}$ refers only to the *mean* accretion rate, i.e. a system is assumed to be transient if steady disk flow with an accretion rate equal to the mass transfer rate is unstable. Our considerations here would only be affected if this (hypothetical) steady flow was itself advection–dominated. In this case there would clearly be no question of irradiation stabilizing the disc. Thus our conclusion that black hole disks are unstable because the fundamental property of these objects weakens the irradiation effect would be still more strongly justified.

5.   CONCLUSIONS

Irradiation of the accretion disk surface by the central source has a determining effect on transient behavior. In neutron–star low–mass X–ray binaries this confines transient behavior to systems with extremely low accretion rates. The very strong formation constraints for neutron–star binaries with low–mass companions nevertheless mean that a significant fraction of these systems are transient. The much weaker contraints on forming black–hole systems would at first sight suggest that very few of them would have mass transfer rates low enough to be transient. The fact that the vast majority of black–hole candidates are nevertheless transient shows that irradiation is weakened by the fundamental property that black holes have no hard surface; that is, they are black.

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FIGURE CAPTIONS

Fig. 1.— Minimum ratio M_1/M_2 (hence lower limit on the BH mass M_1) for SXT behavior in BLMXBs with giant donors as a function of orbital period P (in days), for different donor mass (upper solid line: $M_2 = 2M_\odot$, lower solid line: $M_2 = 1M_\odot$), assuming $\zeta_{eq} = 0$. Mass transfer stability ($\zeta_{eq} > \zeta_L$) requires that M_1/M_2 is above the dashed line. Systems evolve towards longer orbital period and larger M_1/M_2. The evolutionary track for the sequence shown in the lower left panel of Fig. 2 is indicated by a dotted line.

Fig. 2.— Mass transfer rate $\dot{m} = -\dot{M}_2/(M_\odot \mathrm{yr}^{-1})$ (solid curves) and the corresponding critical mass transfer rate $\dot{M}_{cr}$ (dashed) as a function of orbital period P (in days) along various evolutionary sequences of long–period BLMXBs with giant donors. Systems are transient if the track is below the dotted line. The initial BH mass is $10M_\odot$ in the upper panel, $2M_\odot$ in the lower panel. The initial core mass is $M_c = 0.20M_\odot$ and $0.37M_\odot$ for the sequences on the left and right, respectively. Mass transfer begins with a $1.5M_\odot$ secondary and terminates when $M_2 = M_c$ (constant total mass and $\zeta_{eq} = 0$ was assumed).

Fig. 3.— Mass transfer rate $\dot{m} = -\dot{M}_2/M_\odot \mathrm{yr}^{-1}$ versus orbital period P (in h) for short–period BLMXBs with an unevolved secondary of initial mass $1M_\odot$ for different initial primary masses ($2M_\odot$, $5M_\odot$, $10M_\odot$, from top to bottom). The total binary mass is constant along the sequence. Magnetic braking is assumed to operate only as long as the secondary has a radiative core. The smaller contrast between the angular momentum losses above and below the period gap for increasing BH mass means that the detached phase at $P \simeq 3$ h ("period gap") is narrower, and also that the minimum period is longer. The dashed curve represents the critical mass transfer rate for BH accretors. Systems with lower mass transfer rates are transient. Also shown is the critical mass transfer rate for neutron star accretors (dotted; assuming $\eta = 0.15$) and unirradiated disks (dash-dotted).
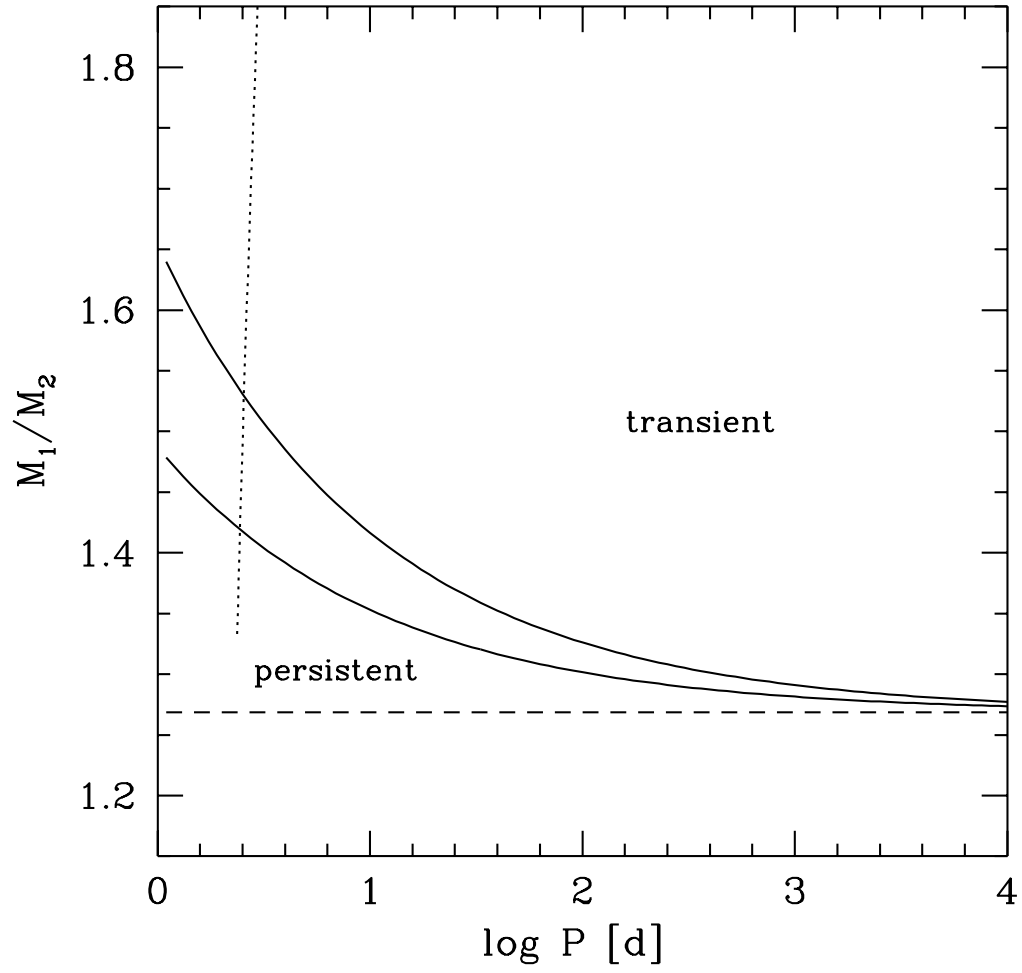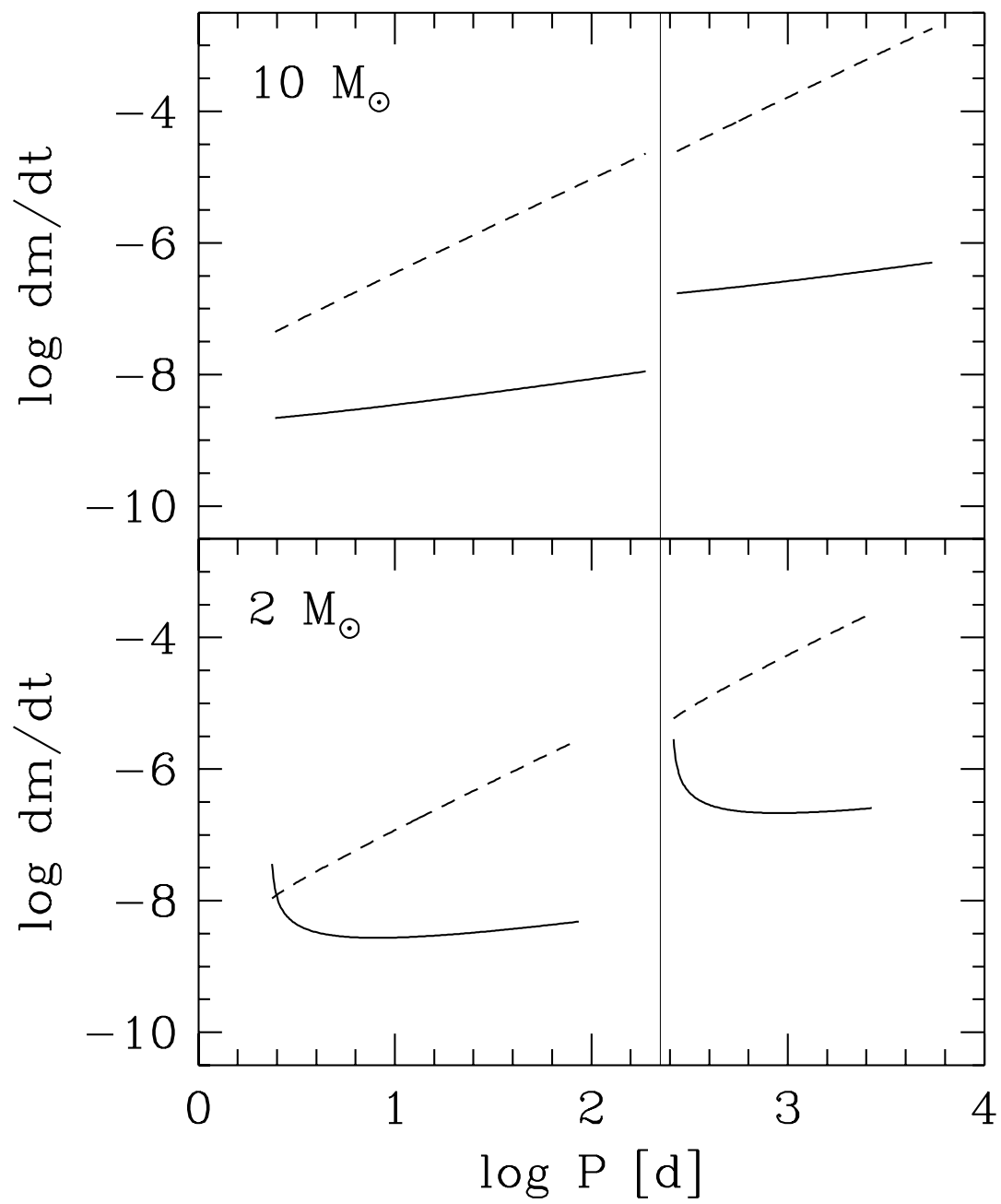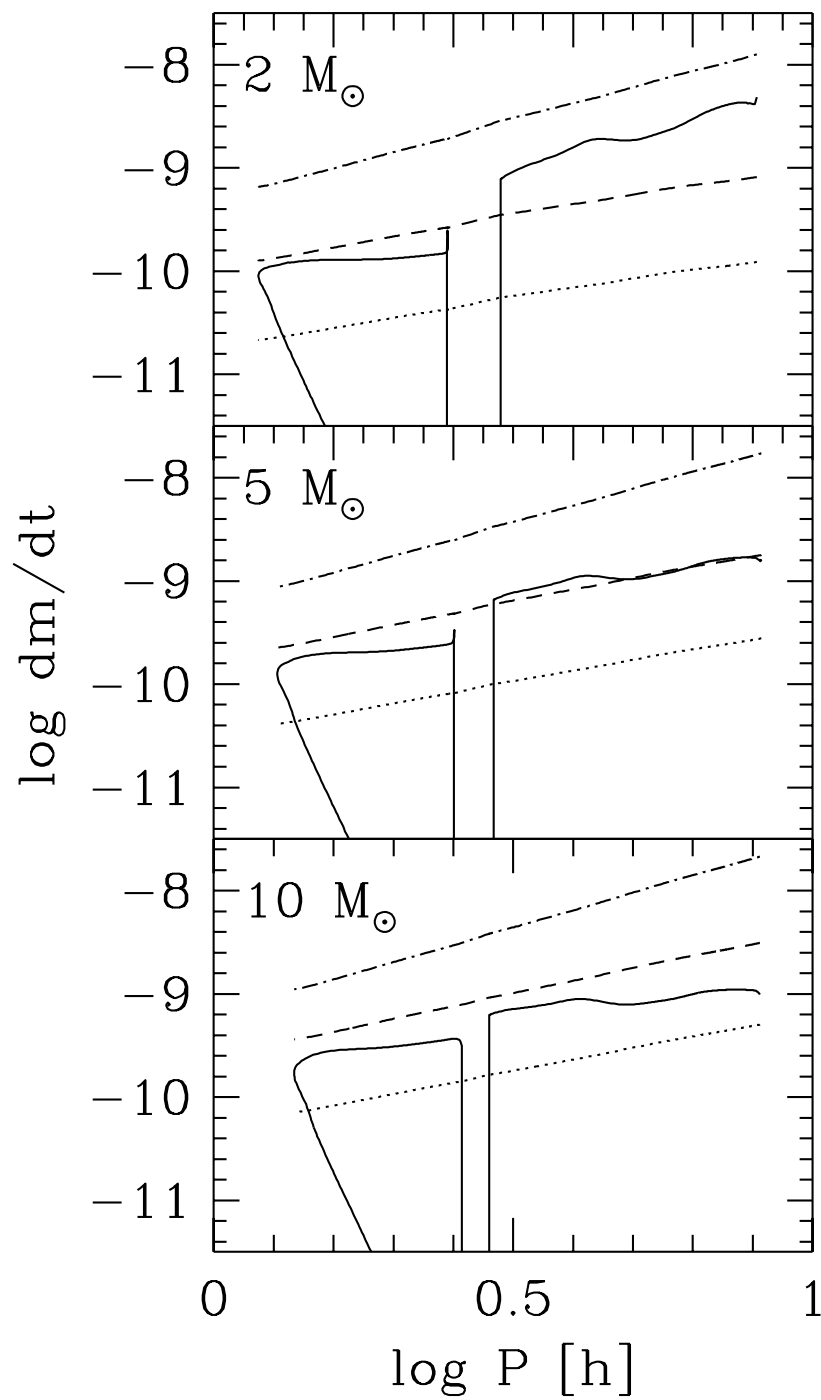
Figure 1

Figure 2

Figure 3